Ontario

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A Flakiness Test for Fine Aggregate

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Abstract	The presence of excessive amounts of flakey particles in the coarser fractions of fine aggregate is thought to be the cause of two cases of 'Uncompactable Hot Mix Asphalt' that have occurred in Canada. This paper describes the development of a test for measuring the amount of flakey particles in fine aggregate. Commercially available slotted sieves for testing grain or seeds are used. Material in the pass 4.75 mm to 2.36 mm fraction is tested on a 1.8 mm slotted sieve and material in the pass 2.36 mm to 1.18 mm fraction is tested on a 1.0 mm slotted sieve. The equipment is inexpensive and the test is not excessively time consuming. High amounts of flakey particles in a manufactured sand or crusher screenings may warn of difficulty in compacting asphalt mixtures in which the material is used by itself as the fine aggregate. Caution should be exercised with fine aggregates that contain amounts of flakey particles (as defined by the test method) in excess of 30% in the 1.18 mm fraction and in excess of 25% in the 2.36 mm fraction. These suggested limits only apply when such aggregates are the sole fine aggregate in the mixture. The measurement of flakey particles may also be used to compare the effect of different crushers and crusher systems on creation of flakey particles in fine aggregate.
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Executive Summary

The presence of excessive amounts of flakey particles in the coarser fractions of fine aggregate is thought to be the cause of two cases of 'Uncompactable Hot Mix Asphalt' that have occurred in Canada. This paper describes the development of a test for measuring the amount of flakey particles in fine aggregate. Commercially available slotted sieves for testing grain or seeds are used. Material in the pass 4.75 to 2.36 mm fraction is tested on a 1.8 mm slotted sieve, and material in the pass 2.36 to 1.18 mm fraction is tested on a 1.0 mm slotted sieve. The equipment is inexpensive, and the test is not excessively time consuming.

High amounts of flakey particles in a manufactured sand or crusher screenings may warn of difficulty in compacting asphalt mixtures in which the material is used by itself as the fine aggregate. Caution should be exercised with fine aggregates that contain amounts of flakey particles (as defined by the test method) in excess of 30% in the 1.18 mm fraction and in excess of 25% in the 2.36 mm fraction. These suggested limits only apply when such aggregates are the sole fine aggregate in the mixture.

The measurement of flakey particles may also be used to compare the effect of different crushers and crusher systems on creation of flakey particles in fine aggregate.

Introduction

In 1996, a hot mix asphalt-paving contractor working near Ottawa, Ontario encountered what he described as an "uncompactable mix". The mix had been designed using the Marshall Mixture Design process and was what is called, in Ontario, a Heavy Duty Binder Mix. This is an asphalt base course mix made with 100% crushed aggregates, both coarse and fine. The aggregates are manufactured from quarried bedrock sources. This mixture is commonly used in Ontario and was developed to resist rutting on freeway pavements where there was very heavy truck use that would otherwise cause wheel path rutting. In this case, the contractor had designed the mixture in his own laboratory, which was well equipped and had extensive asphalt mixture design experience.

The mixture consisted of about 50% by mass of well-graded coarse aggregate (> 4.75 mm) of quarried dolostone of the Oxford Formation with the fine aggregate consisting of manufactured sand from the same source. The materials met and exceeded all relevant material specifications. The experienced paving crew were unable to obtain the required compaction in the field. A variety of solutions was sought. Various combinations of paving and compaction equipment and rolling patterns were tried to no avail. Changes in layer thickness or temperature did not work. The coarse aggregate was substituted for another, with no success. The ultimate solution was found to be to substitute the dolostone fine aggregate with manufactured sand from a limestone quarry. After a redesign of the mixture, paving took place with no problems, and adequate compaction was achieved.

We were asked to look at the dolostone fine aggregate to see if there was any characteristic that might indicate the cause of the problem. An examination under the microscope showed that the particles retained on the 1.18 and 2.36 mm sieves contained large amounts of flakey particles. The number of flakey particles in the limestone sand was less, and the particles were not so obviously flakey or sharp.

At this point, we started to look for a cheap, easy, and practical test that might be used as a tool in the normal commercial mix design laboratory to warn of, or indicate, manufactured sands that were extremely flakey and might contribute to or cause lay down or compaction problems. More recently, the focus of researchers has been on image analysis techniques (Masad *et al* 2007). The sophistication of the equipment is such that it can rarely be justified in a commercial asphalt mixture design laboratory and is not commonly available.

TEST METHOD DEVELOPMENT

The first test that was looked at was the test for flat and elongated particles. In Ontario, a hand-held set of proportional callipers set in ratio of 4:1 is used. Unlike the conventional 'Army Corps of Engineers' callipers used in ASTM D4791, the hand-held callipers are capable of being used to fairly easily measure proportions of particles retained on the 2.36 mm sieve. However, the quality of manufacture is such that a great deal of operator experience is needed, and there are variations in the accuracy of different callipers.

It was known that the coarse aggregate version of the method had extremely poor multi-laboratory variation. It was desired to devise a piece of test equipment that would be accurate, reduce the effect of operator influence, and give reproducible results in different laboratories. For this reason, this test was not pursued further.

We also examined the Uncompacted Voids Test (ASTM C1252). This test has lower limits for acceptable asphalt paving aggregates but no upper limits. No suitable upper value could be easily identified that would not result in possible rejection of materials which might perform satisfactorily while rejecting those that gave a mixture with poor compaction characteristics.

In the United Kingdom, there is a flakiness test used on coarse aggregate (Photo 1) and special slotted sieves that are commercially available, which are used to determine if particles are deemed by the test method definition to be flakey. In the British Standard (BS 812), they define the slot dimensions through which flakey particles will pass as 0.6 of the mean size between two consecutive sieves. For instance, for a sieve fraction of pass 6.3 mm and retained on 4.75 mm, the mean size is 5.53 mm. 5.53 x 0.6 = 3.3 mm. Coarse aggregate is first sieved to refusal on a square opening sieve of 4.75 mm, and then the material retained on that sieve is re-sieved on the flakiness sieve of the appropriate slot size (3.3 mm in this case). In actual practice, manipulation or examination of each particle takes place to determine if it can be fitted through the slot. Material that passes the slot is defined as a flakey particle, and the proportion of these are expressed as a per cent by mass of the original material retained on the square opening sieve. There are no known slotted flakiness sieves for fine aggregates and, indeed, the British Standard says that this test is not applicable to material passing a 6.30 mm sieve.

We had a machine shop make slotted sieves in a variety of sizes. This was done by taking a solid billet of steel approximately 100 mm square and 30 mm deep. Using an extremely accurate computer-controlled wire cutter, slots were cut in the solid steel to the required size. To create a suitable hollow to contain and hold particles, the steel billet was then milled out, leaving a thin base of about 2 mm thickness and solid steel sides. Each sieve made this way costs about $500. It was also not a process that would be easily amenable to mass production.

Early investigations were conducted on sieves made in this way. One of the problems that immediately became apparent was the need to obtain representative specimens from bulk samples. It was found that, after sieving by hand on the slotted sieves, there was still a need to inspect and sometimes manipulate each particle with a pair of tweezers to see if it would fit through the slot. Flakey particles lie flat on the sieve surface and do not easily present their edges to the slots. Many flakey particles will fall through during hand sieving, but not all. The consequence is that, if the sample is large, the number of particles that have to be individually examined becomes very large and the task is tedious. In an effort to reduce the burden of testing, a spinning riffler was purchased so that small representative test samples could be accurately made.

In a spinning riffler system, materials are fed from a hopper in a narrow stream onto a slow-moving vibrating feeder. The feeder discharges into identical sample containers or test tubes placed on a spinning turntable. It takes approximately 30 passes under the stream of aggregate from the feeder to fill each test tube to capacity. The number of passes depends on feeder speed,

turntable speed, and desired sample size. One or more of the filled test tubes can be further subdivided using the same technique. This results in a more representative sample than could be obtained using any other technique. Spinning rifflers are capable of removing the effects of segregation in a material stream by the use of multiple passes to acquire the sample. The process will work best if the turntable turns relatively quickly and the flow of material is relatively slow so as to maximize the number of passes needed to acquire a sample.

Following the British Standard definition for the fraction from 4.75 to 2.36, the mean size is 3.55 mm. 3.55 mm x 0.6 = 2.13 mm. This size seemed to pass too much material and, as a result, a variety of smaller slotted sieves was tested to understand more fully some of the relationships. A ratio of 0.75 of the retaining sieve was finally chosen, which is 2.36 mm x 0.75 = 1.77 (or 1.80 mm). We also evaluated a size of 1.42 mm that was developed from 2.36 mm x 0.60 = 1.42 mm slot size. The 1.0 mm and 1.70 mm sieves were also used because they were available. The results of testing a variety of fine aggregates are shown in Table 1. Figure 1 shows graphically how the amount of flakey particles varies as a function of slot or flakey sieve opening for material passing the 4.75 mm sieve and retained on the 2.36 mm sieve.

Table 1 also shows the same relationship for material pass the 2.36 mm sieve and sieved to refusal on a 1.18 mm sieve and then sieved over slotted sieves of various sizes. For the 2.36 to 1.18 mm fraction, the mean size is 1.77 mm. 1.77 mm x 0.6 = 1.06 mm, which is the size needed if the British definition of a 0.6 ratio of the mean opening size is used. For the same fraction, but calculating the slot size using the ratio of size of the retaining sieve would give 1.18 x 0.6 = 0.71 mm. If the same rationale as used for the 2.36 mm fraction was used for the 1.18 mm fraction, a flakiness sieve of 1.18 x 0.75 = 0.89 mm would be needed. In Figure 2, a graph of flakey particles as a function of slot opening is shown for the 1.18 mm fraction. A flakiness sieve (1.42 mm) developed for testing the 2.36 mm fraction was also used since it was available. As was expected, very large amounts of material passed this sieve and the majority could not properly be defined as flakey particles since they were often smaller non-flakey, or roughly equidimensional, particles found in the sieve fraction.

In both graphs, it is noteworthy that there is an apparent straight-line relationship between the size of the slot and amount passing. The exception is in Figure 1 for the 1 mm slot for the retained 2.36 mm fraction where very few particles passed the slot.

After this development work had been carried out, we became aware that slotted sieves used for testing seeds and grain were commercially available at a reasonable cost (Photo 2). These were made from punched plate and were available from 1 mm upwards in 0.1 mm increments. A decision was made at this point to arbitrarily focus on one slot size for each fraction. For the 2.36 mm fraction, the 1.80 mm size was chosen (Photos 3 and 4) and, for the 1.18 fraction, the 1.00 mm slot size sieve was chosen. When the 1.80 mm size is chosen, it is a ratio of 0.75 of the retaining sieve (2.36 mm). A similar sieve would have been chosen for the 1.18 mm fraction that is 0.89 mm. However, the lack of commercial availability of that size swayed the decision to use the smallest commercially available slotted sieve of 1.0 mm. It is realized that this choice was arbitrary, but the search was for a practical and low cost test that would warn asphalt mix designers of potential problems.

Figure 3 shows the relationship with the percent flakey particles in the 2.36 mm fraction with the per cent flakey particles when the 1.0 mm and 0.89 mm slotted sieves are used for testing the 1.18 mm fraction. Significantly, there is a better correlation with flakey particles in the 2.36 mm fraction (using the 1.8 mm slot) when the 1.0 mm slotted sieve is used, further justifying the choice of the commercially available 1.0 mm slotted sieve for that fraction rather than the 0.89 mm sieve.

SAMPLE COLLECTION

We collected about 120 samples of aggregates used in concrete and asphalt from across Ontario. This included natural glacio-fluvial sands composed substantially of rounded and sub-angular particles; mixtures of natural sands and crusher screenings; and samples composed exclusively of crusher screenings or manufactured sands. Most of these had a history of being used in either asphalt or concrete or both. The composition of the fine aggregates varied from those composed of 100% siliceous rock types from the central and northern parts of the province to those of 100% carbonate rock from the south, as well as of mixtures of both carbonate and siliceous rock types in natural sands. The sample collection was broad enough that samples of most of the fine aggregates likely to be encountered in Ontario were represented. A variety of crusher types and crushing set-ups was also represented.

TESTING PROGRAM

The sands were tested in a variety of tests:

1. The Fine Aggregate Micro-Deval Test now published by ASTM as D7428-08,
2. Bulk density and water absorption following ASTM C128,
3. Aggregate uncompacted voids using method A and B following ASTM C1252,
4. Flakey particles (in per cent) using the test described in this paper and described in detail in Appendix 1, and
5. Compacted Aggregate Resistance Test (CAR) following the proposal of D. Jahn using a simplified method (2004) described in Appendix 2.

RESULTS AND DISCUSSION

Figure 4 shows a plot of flakey particles in the 1.18 mm fraction compared with flakey particles in the 2.36 mm fraction. As might be expected, fine aggregates that have a lot of flakey particles in one fraction tend to have a lot in the other fraction. However, regression coefficients are not strong and have been omitted from this plot for clarity. As might be expected, natural sands tend to have a lot less flakey particles than crusher screenings. There are some crusher screenings that plot in the field of the natural sands, and it is suspected that these may be mixtures of natural sand and crusher screenings. Further microscopic study is needed. It is noteworthy that no natural sands have large numbers of flakey particles (> 25%). Also plotted on this graph is the screenings sample labelled as 'Oxford dolostone', which first raised the issue of uncompactable mixtures. It can be seen that this material contained over 30% flakey particles in both sieve fractions. Also plotted is a material labelled as 'Amabel dolostone'. This material is of Silurian age from the Niagara Escarpment and is a high purity reefal dolostone. This material has a long history of use in 'Heavy Duty Binder Mixes', where 100% crushed coarse and fine aggregate is used in asphalt base course. This material had flakey particles of about 20% in both fractions and has given good

performance. In about 2002, we became aware of another case of a suspected uncompactable mix. This occurred in the province of New Brunswick, and some of the physical characteristics of the rhyolitic fine aggregate are summarized in Table 2, together with those for the Amabel dolostone. This data is shown graphically in Figure 4. It is noteworthy that this material had a very high amount of flakey particles and reportedly gave problems with compaction similar to those described in the introduction that occurred in Ontario.

Tentative limits are drawn on the graph of 30% for the 1.18 mm fraction and 25% for the 2.36 mm fraction. We speculate that, when crusher screenings are found with values in excess of both of these values, and the materials are used by themselves in a 100% crushed aggregate asphalt mixture, there is an increased likelihood that compaction issues may arise. This warning does not necessarily apply if the crusher screenings/manufactured sand is blended with either natural rounded sand or manufactured sand with a low amount of flakey particles.

To obtain further information about this issue and the possible limits that may act as a warning, further experiences with uncompactable or hard to compact mixtures will have to be gained. These are apparently rare, and the likely cause may be overlooked.

Figure 5 shows a plot similar to that of Figure 1 but, in this case, three concrete sands have been plotted. Two of these sands (Caledon and Redmond) have a long history of extensive satisfactory use in hydraulic cement concrete. It is noteworthy, but not unexpected, that they have low amounts of flakey particles compared to the crusher screenings/manufactured sands. If they did have a very flakey nature, the negative effect on water demand would probably be such that they would not be economically used in their respective market areas. The third sand 'Axim' is a standard concrete sand used by a chemical supply company for testing admixtures.

Figure 6 shows the mean amount of flakey particles (50% of each fraction used in the calculation) plotted against the Uncompacted Voids Content of ASTM C1252, Method A. Generally, using the Superpave mixture design process, it is desirable to use fine aggregates that have a voids content of greater than 45 or 43 (in some cases) for high ESAL asphalt pavements. It can be seen that, generally, natural sands gave values less than about 44 and the crusher screenings/ manufactured sands values in excess of this. It is notable that there is not a strong relationship between voids value and amount of flakey particles. Crusher screenings with voids value in the 48 range can have flakey particle contents that range from about 11% to 40%. If the voids value predicts stability of asphalt mixtures, it certainly will not warn of the presence of high amounts of flakey particles. The two tests are measuring different properties, and both should be considered when evaluating a crusher screenings for use in asphaltic concrete.

The Uncompacted Voids Content Test was originally developed by the National Crushed Stone Association (Gray and Bell, 1964) for predicting finishability of concrete sand. As there is increasing use of manufactured sands in this application, it may well be useful to also look at the amount of flakey particles present in the manufactured sand, as Figure 6 clearly shows that voids by itself does not reliably predict flakey particle content.

With more equidimensional (less flakey) aggregate, the optimum asphalt content will normally be reduced due to a better packing density and lower internal surface area. Therefore, it would be useful to measure the amount of flakey particles of crusher screenings to choose those sources of supply that contain the least amount, other things being equal. This would be beneficial when high amounts of crusher screenings or manufactured sands are being used in an asphalt mixture.

Figure 7 shows the results of testing three samples of crusher screenings from the same quarry over four years. The material was a hard diabase of Precambrian age (Huronian). In 1996, the quarry operator was using a different crusher than was used in 1998 and 1999. The production of crusher screenings from 1996 had significantly more flakey particles than that produced with the different crushers in 1998 and 1999. The crusher used in 1996 was reported to be a vertical shaft impact crusher that had been brought in to improve shape of the coarse aggregate. The crushers used in later years were a more conventional series of cone crushers. The Flakiness Test may be useful for evaluating shape of fine aggregate produced by different types of crusher and by different reduction ratios. Further study is needed.

Figures 8 and 9 show relationships of water absorption and flakey particles as a function of fine aggregate micro-Deval loss. No obvious relationships can be observed, which is not unexpected. However, flakiness of fine aggregate from a single aggregate source may influence micro-Deval loss. For instance, flakey particles may be more easily abraded in the rotating drum than cubical particles from the same source.

Figure 10 shows the relationship between flakey particles and the Compacted Aggregate Resistance Test (Jahn, 2004). The CAR Test is done by measuring the resistance to embedment of a metal cylinder on aggregate compacted in a Marshall mold normally used for asphalt mixture design purposes (see Appendix 2). The values obtained are thought to be related to shear resistance of the compacted sand. Low CAR values indicate relatively low shear resistance; high values indicate relatively high shear resistance. This figure shows that shear resistance is apparently unrelated to the amount of flakey particles. Other properties such as surface texture and roundness must be more important. As expected, the natural sands that generally have a rounded and polished texture all gave relatively low CAR stability (lower shear strength). Conversely, not all crusher screenings gave high CAR values.

Figure 11 shows the relationship between Uncompacted Voids and the CAR Test values. It is noteworthy that there were no sands or screenings with low voids values (< 45) that gave high CAR values. Whether or not the CAR Test can be used in place of the Uncompacted Voids Test as suggested by Jahn (2004) is unknown, but there does appear to be a relationship between the two different tests.

Conclusions

The measurement of the amount of flakey particles in the coarse fractions of fine aggregate is simple and inexpensive. The slotted sieves necessary to do this are commercially available.

High amounts of flakey particles in a fine aggregate may warn of difficulty in compacting asphalt mixtures in which the material is used by itself as the fine aggregate. Two known cases of such mixes have been briefly documented, and the responsible fine aggregates had amounts of flakey particles (as defined by the test method) in excess of 30% in the 1.18 mm fraction and in excess of 25% in the 2.36 mm fraction.

Materials that have uncompacted voids (ASTM C1252, Method A) contents in excess of 45 may have either high or low amounts of flakey particles. Thus, the ASTM test does not necessarily warn of a potential compaction problem due to particle shape.

The Flakiness Test may be useful for comparing the shape of crusher screenings produced using different crusher types or using different reduction ratios.

The Compacted Aggregate Resistance Test is not related to the proportion of flakey particles in a fine aggregate, and cannot be used to predict problems caused by the presence of excessive amounts of flakey particles.

There is a relationship between the ASTM Uncompacted Voids value and the CAR Test.

There is a need to gain experience with this proposed test in a variety of laboratories and applications. It is thought that this test would never be suitable in a material specification. It might be used by people selecting sources of material, as a screening test, to indicate potential problems related to excessive amounts of flakey particles. It can also be used to compare the effect of different crushers and crusher systems on generation of flakey particles in fine aggregate. The authors welcome feedback on the utility of the test.

Acknowledgements

We wish to acknowledge the assistance of Bert Hendriks of Tomlinson Construction of Ottawa, Ontario, who first investigated the problem with an uncompactable asphalt mix and recognized the probable contribution of the flakiness of the manufactured sand to his problem. Mike MacKay, of JEGEL in Toronto, gave information on the case in New Brunswick. Everton Arnold and Mark Vasavithasan provided assistance with conducting and interpreting the results from the CAR Test. Steve Senior took the photographs. We also wish to acknowledge the hard work of the staff of the Soils and Aggregates Section of the Ministry of Transportation who conducted the testing and other staff of the ministry Aggregate Units who collected the samples throughout Ontario.

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Table 1. Data demonstrating how per cent flakey particles in fine aggregate varies as a function of slot size used to define flakey particles.

Sample Description	Slot opening of Flakiness Sieve for Testing 4.75-2.36 mm Fraction	Per cent Passing the Slotted Sieve	Slot opening of Flakiness Sieve for Testing 2.36-1.18 mm Fraction	Per cent Passing the Slotted Sieve
Limestone Bobcaygeon Formation, quarry source Satisfactory performance	1.80	20.14	1.43	61.64
	1.70	15.52	1.00	26.27
	1.42	1.46	0.81	13.26
	1.00	0.47	0.71	3.64
Dolostone Oxford Formation, quarry source Uncompactible	1.80	30.27	1.43	65.26
	1.70	25.82	1.00	32.43
	1.42	10.95	0.81	18.72
	1.00	1.85	0.71	5.02
Metavolcanic Mine waste, quarry source Satisfactory performance	1.80	28.43	1.43	62.11
	1.70	24.50	1.00	28.11
	1.42	9.24	0.81	14.43
	1.00	1.84	0.71	3.76
Dolostone Amabel Formation, quarry source Satisfactory performance	1.80	28.39	1.43	61.51
	1.70	21.35	1.00	24.06
	1.42	5.70	0.81	10.92
	1.00	0.80	0.71	2.73
Dolomitic Sandstone March Formation, quarry source Satisfactory performance	1.80	19.65	1.43	60.60
	1.70	15.64	1.00	22.83
	1.42	5.16	0.81	11.12
	1.00	0.44	0.71	2.78
Sand with crusher screenings No history of use	1.80	28.78	1.43	73.07
	1.70	24.36	1.00	34.24
	1.42	11.02	0.81	17.85
	1.00	2.29	0.71	5.43

Table 2. Properties of fine aggregates of effect of particle shape on compaction properties and stability of asphalt. Tested by MTO laboratory, January 2002.

	New Brunswick Screenings, Poor Compactability	Amabel Dolostone, High Stability Manufactured Sand, Satisfactory Performance
ASTM C1252 Method A	51.1	44.5
ASTM C1252 Method B		
for 1.18 mm	53.5	49.6
for 600 µm	56.0	51.1
for 300 µm	55.9	51.3
ASTM Method B, Mean	55.1	50.7
Flakey Particles, %		
4.75 - 2.36 mm on 1.80 mm	25.4	22.0
2.36 - 1.18 mm on 1.00 mm	41.0	20.7

Photo 1. British Standard 812 flakiness sieve for older Imperial sieves.

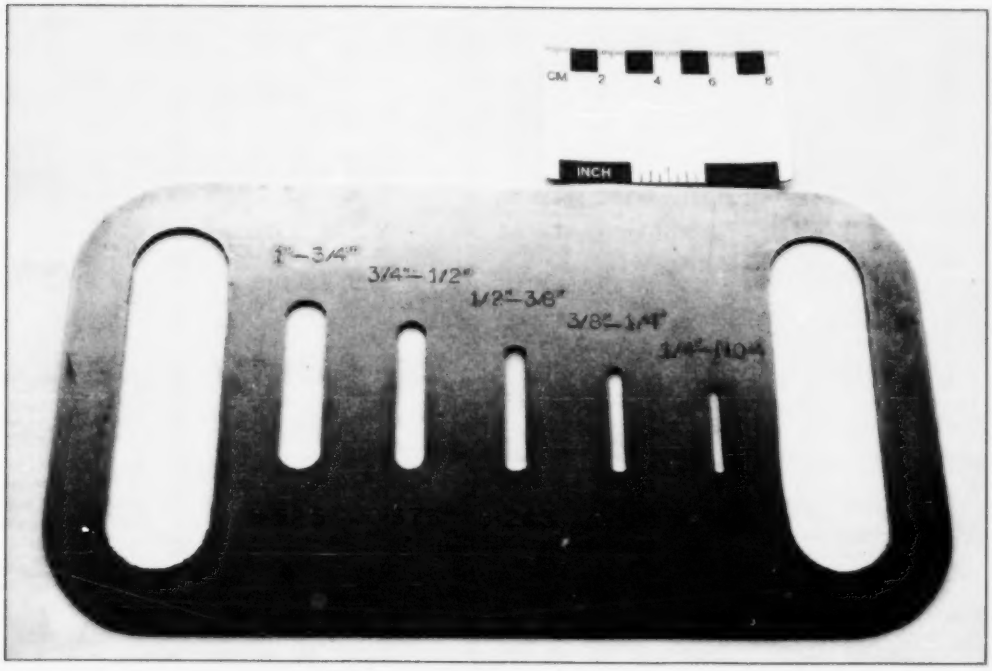


Photo 2. Slotted sieves used in the testing described in this paper.

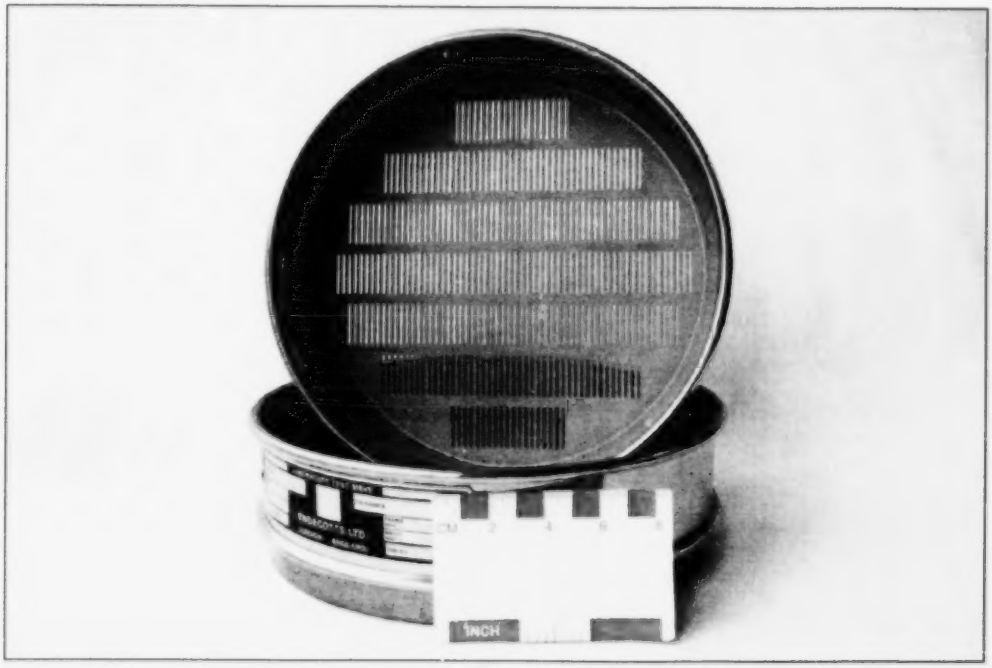


Photo 3. Aggregate particles retained on the 1.80 mm slotted sieve (scale in cm).

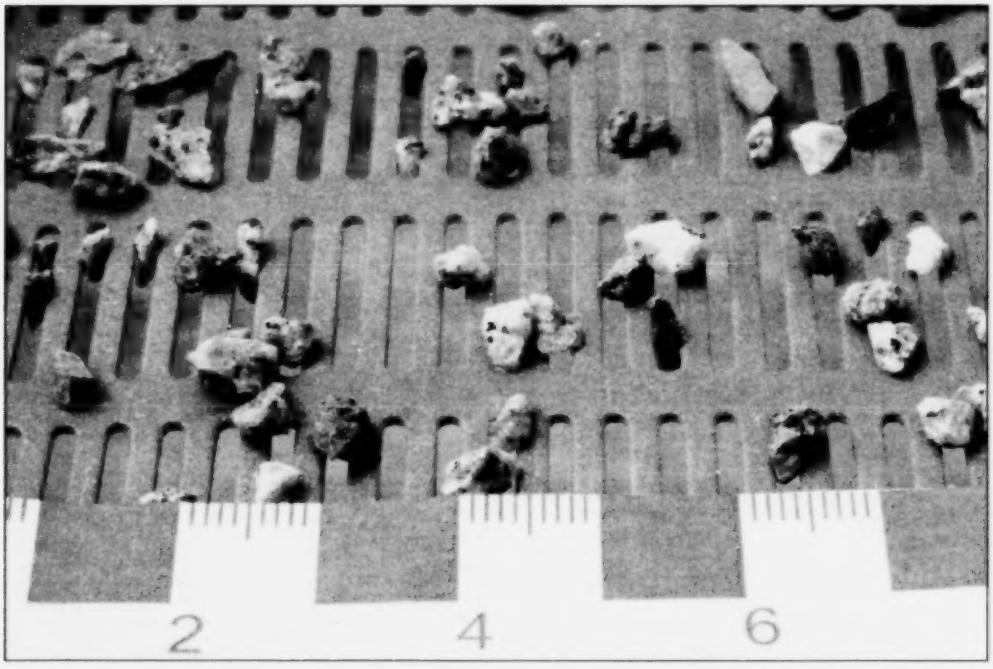
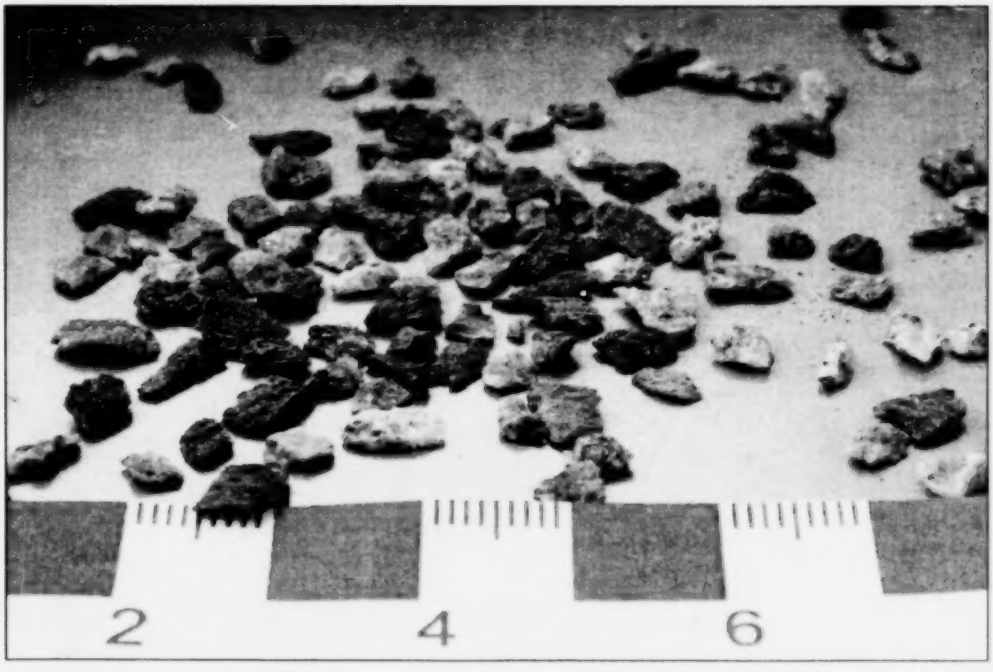


Photo 4. Flakey particles that passed through the 1.80 mm slots (scale in cm).



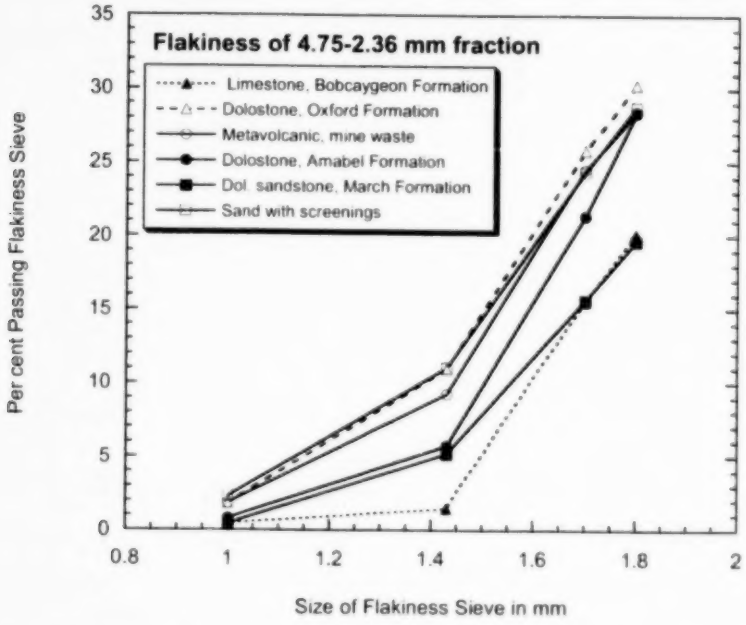


Figure 1. Variation of flakey particles with size of slotted sieve for the 2.36 mm fraction.

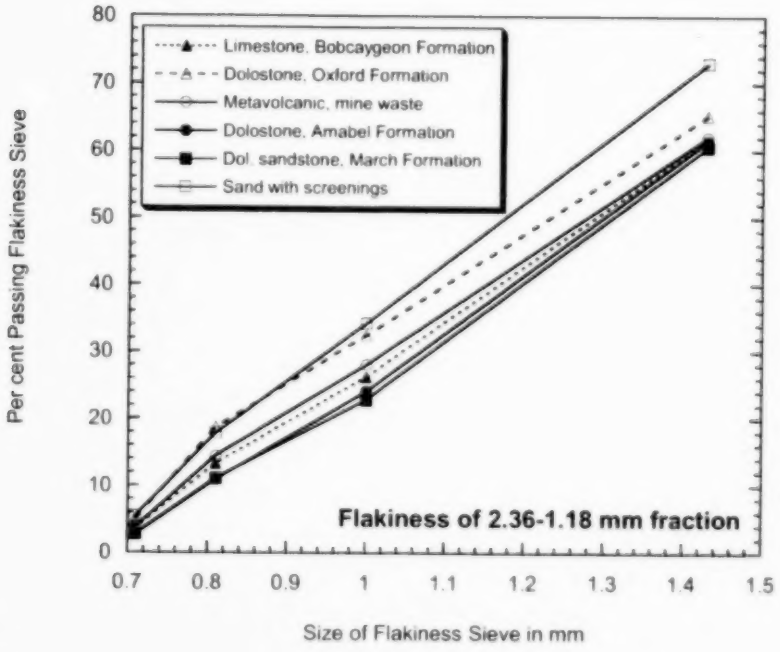


Figure 2. Variation of flakey particles with size of slotted sieve for the 1.18 mm fraction.

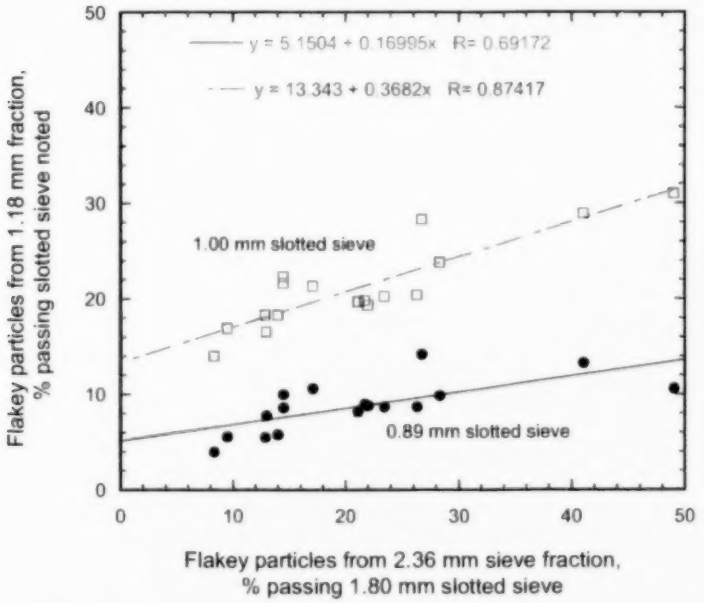

y = 5.1504 + 0.16995x R= 0.69172
y = 13.343 + 0.3682x R= 0.87417
1.00 mm slotted sieve
0.89 mm slotted sieve
Flakey particles from 1.18 mm fraction, % passing slotted sieve noted
Flakey particles from 2.36 mm sieve fraction, % passing 1.80 mm slotted sieve
0
10
20
30
40
50

Figure 3. Correlation between flakey particles of 1.18 mm size on various slotted sieves and flakey particles of 2.36 mm size using a 1.80 mm slotted sieve.

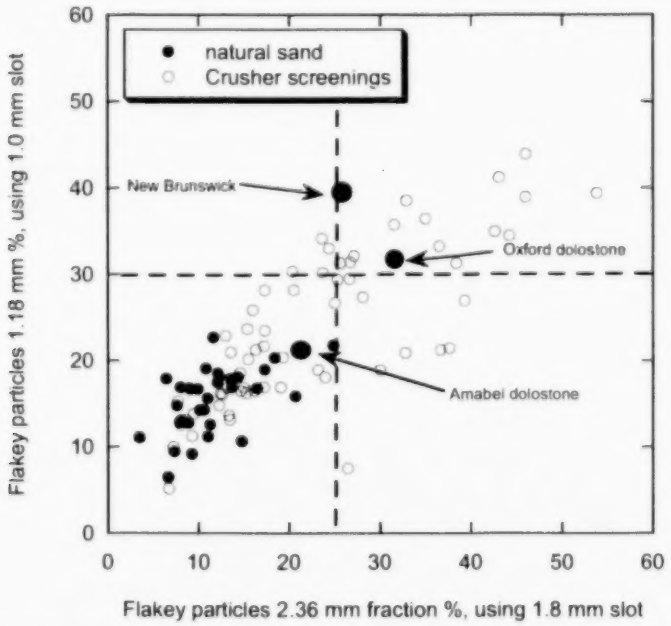


Figure 4. Comparison between flakey particles of 1.18 fraction with 2.36 mm fraction.

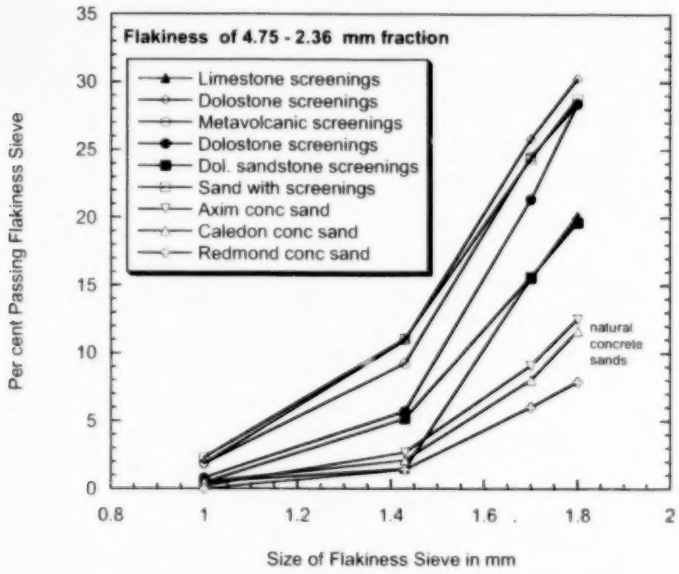


Figure 5. Comparison of flakey particles in sand and crusher screenings.

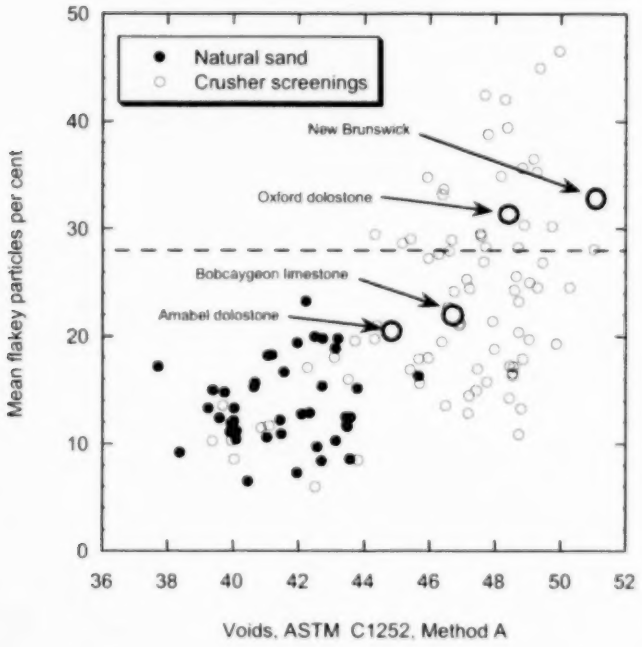


Figure 6. Mean flakey particles compared to uncompacted voids.

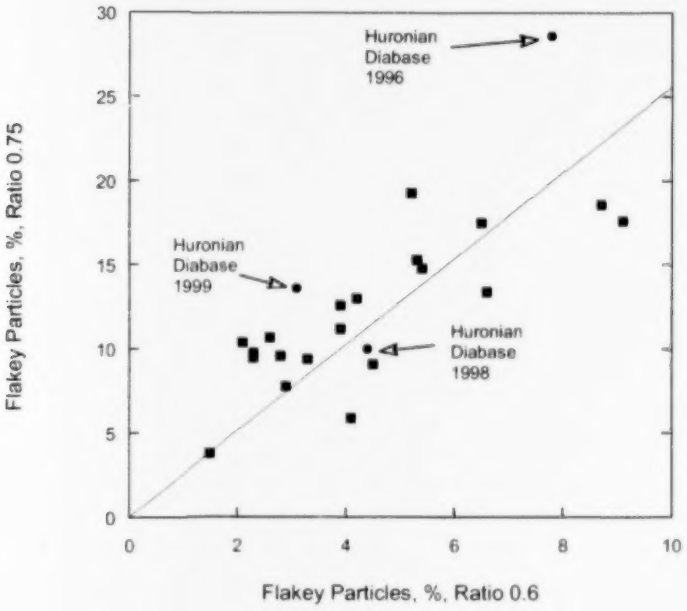


Figure 7. Flakey particles measured at various ratios of the mean sieve size, showing how materials from a quarry vary in amount of flakey particles with different crushers.

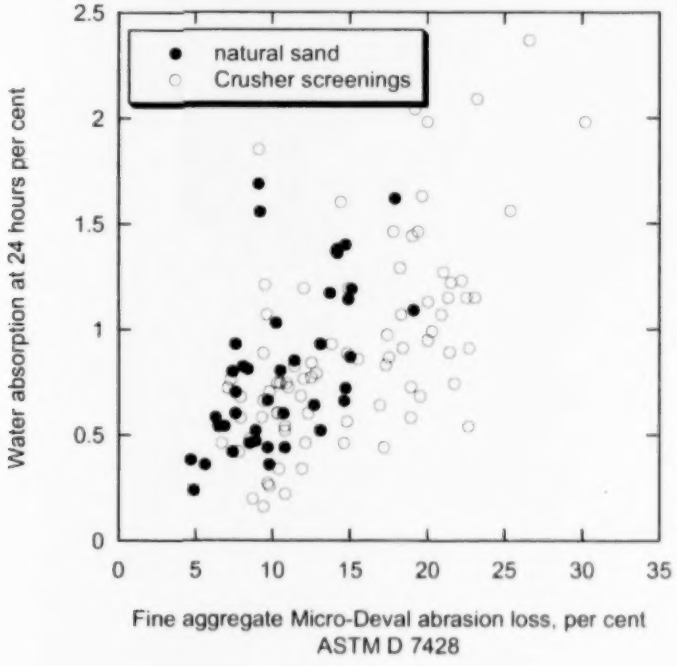


Figure 8. Water absorption compared to micro-Deval abrasion loss.

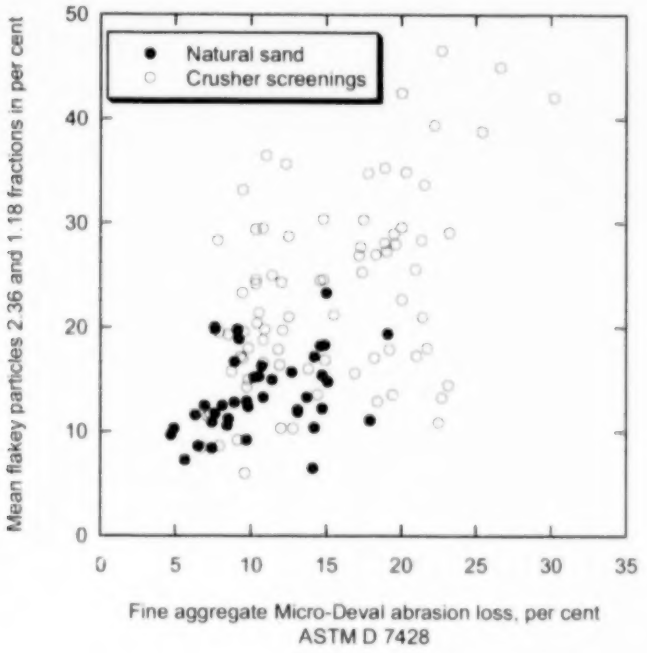


Figure 9. Mean flakey particles compared to micro-Deval abrasion loss.

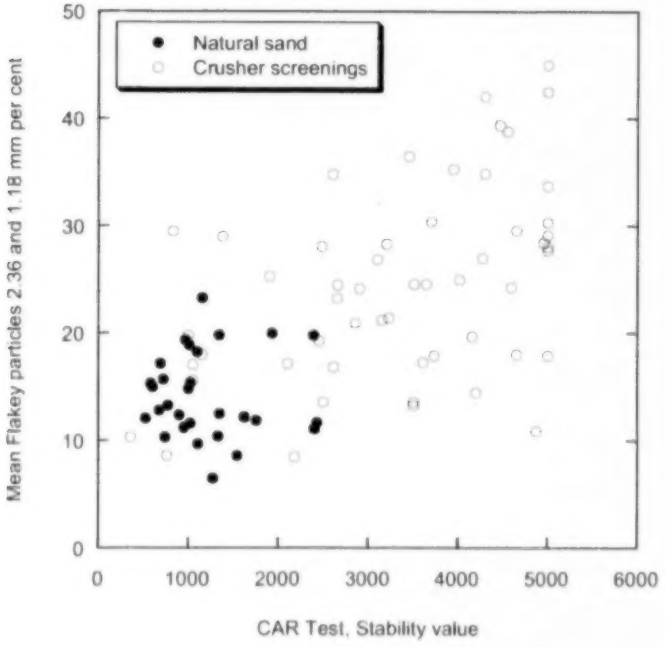


Figure 10. Mean flakey particles compared with CAR stability test value.

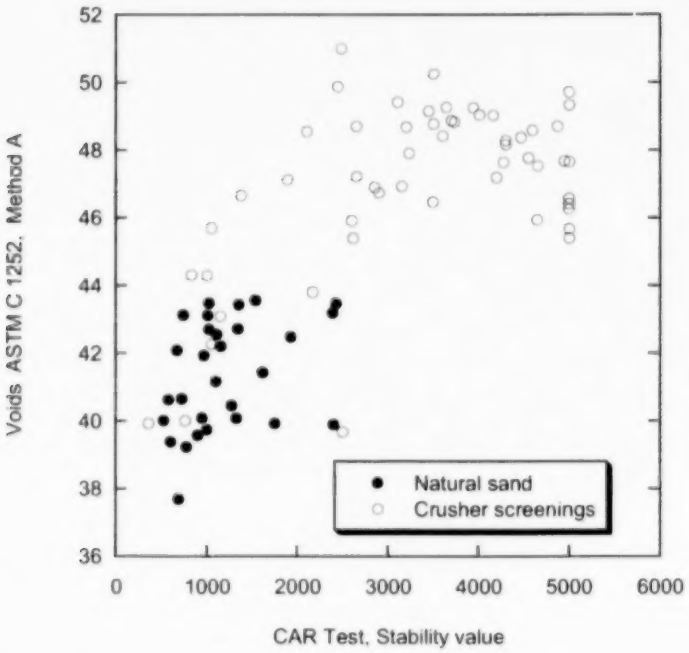


Figure 11. Uncompacted voids compared with CAR stability test value.

Appendix 1

METHOD OF TEST FOR DETERMINING AMOUNT OF FLAKEY PARTICLES IN FINE AGGREGATE

Definition:
Flakey particles for the purposes of this test are fine aggregate particles with a thickness (least dimension) which is equal to or less than 1.8 mm for material passing a 4.75 mm sieve and retained on 2.36 mm, and 1.0 mm for material passing a 2.36 mm sieve and retained on a 1.18 mm sieve.

Significance and Use:
The amount of flakey particles can provide an indication of the ability of the fine aggregate to contribute to ease of compaction in dense graded hot mix asphalt pavements. A large number of flakey particles (> 25%) may indicate a fine aggregate that may result in mixtures that are hard to compact or resist compaction. Sand that is low in flakey particles may indicate a material that will contribute to a lower water demand in hydraulic cement concrete compared to sand with higher amounts of flakey particles. The amount of flakey particles in a fine aggregate may vary, depending on the type of crusher used and the reduction ratio.

Equipment:
Flakiness sieves (Note 1) with a slot that is 1.8 mm for the 4.75 - 2.36 mm fraction and 1.0 mm for the 2.36 - 1.18 mm fraction. The sieves shall have a close fitting cover and pan to prevent loss of material.

Note 1: Slotted sieves for testing seeds are available from Endicott's.

Balance of adequate capacity reading to 0.01 g.

Tweezers will be found useful for manipulation of the samples following sieving.

Suitable equipment for preparing a test sample by either cone and quartering, or the use of a spinning riffler.

Sample:
The required test sample size is as follows: 4.75 - 2.36 mm, minimum 30 g, 2.36 - 1.18 mm, minimum 10 g.

Sample Preparation:
Prepare approximately 50 g of each fraction by sieving washed dry fine aggregate to refusal on the respective woven wire square opening sieve. Prepare by cone and quartering a representative test sample meeting the requirements above. Weigh to 0.01 g and record (Mass A).

Note 2: It is important to avoid segregation of the sample following sieving, but prior to preparing the flakiness test specimen. Splitting, in particular, may not be a good technique because sliding of the particles on a flat surface may cause flakey particles to be retarded in motion compared with the more cubical particles. The ideal technique is to use a small spinning riffler to prepare a representative sample.

Place the sample on the slotted sieve and sieve by hand, using taps with the heel of the open hand on the side of the sieve nested with the lid and pan. After sufficient sieving, so that the majority of flakey particles pass through the slot, inspect the individual particles retained on the slotted sieve to ensure all flakey particles have passed through the sieve (Note 3). When all particles have been individually examined, weigh and record the mass of material that is retained on the flakiness sieve (Mass B).

Note 3: Tweezers will be found useful.

Calculation and Reporting:

Calculate the per cent flakey particles for each fraction as follows: A-B/A x 100 = flakey particles in %.

Report the per cent flakey particles of each sieve fraction to 0.1% and the average of the 2.36 and 1.18 mm fractions in each sample to 0.1%, assuming a 50% contribution by each (Note 4).

Note 4: A weighted average may be calculated based on the grading of the fine aggregate, but suggested limits to separate various performance categories have not been developed.

Figure A1: Reporting Form for Fine Aggregate Flakiness Test

Laboratory Sample Number	Sieve fraction 4.75 - 2.36 mm Original Mass of Sample 'A'	Sieve Fraction 2.36 - 1.18 mm Original Mass of Sample 'A'	Mass of Material Retained on Slotted Sieve 'B'	Flakey Particles A-B/A x 100 Per Cent

Note: Use 1.8 mm slotted sieve for 4.75 - 2.36 mm fraction and 1.0 mm slotted sieve for 2.36 - 1.18 mm fraction.

Date _____ Technician _____

Remarks

Appendix 2

ABBREVIATED TEST PROCEDURE FOR THE COMPACTED AGGREGATE RESISTANCE (CAR) TEST (2004)

The CAR Test evaluates the shear resistance of the blend of fine aggregate materials for HMA, using as received gradations. Useful information can also be obtained by testing individual components.

1. Mixture Preparation:

1.1 Oven dry each fine aggregate material, allow to cool to room temperature, and separate into #4 x #8 and #8 x 0 components.

1.2 Combine components of each fine aggregate material, based on the intended combination of fine aggregates, sufficient to produce a compacted specimen 2.5 in. high in a 4-in. Marshall mold (approx. 1000 g).

1.3 Mix the dry materials in a mixing bowl, crater the mixture, and then add 3.5% moisture. Immediately mix until particles are uniformly coated (about 30 seconds).

2. Mixture Compaction:

2.1 Place entire coated mixture in a room temperature 4" Marshall mold with base plate and collar. Spade 20 times over the mixture with a spatula, trowel, or spoon. Round off the top of the mixture with a spatula, and place two pieces of non-absorbent paper cut to fit on top of the mix.

2.2 Place the mold onto the compaction hammer pedestal, and insert the compaction hammer. Seat the compaction foot on top of the loose mix by raising the sliding weight approximately ½ in. and tap the compaction foot three times.

2.3 Compact the sample using 50 blows, *one side only*, with a Marshall hammer. An automatic hammer has been used to develop this procedure.

3. Shear Resistance Determination:

3.1 Remove the collar, but leave the base plate underneath the compacted sample. Transfer the mold, compacted sample, and base plate, keeping the compacted side up, to the breaking head (modified 6-in. Lottman breaking head). Centre the plunger (1½-in. by 1½-in. cylinder) on top of the compacted specimen, and shear the flat end of the plunger into the compacted specimen using the Marshall Stability and Flow machine.

3.2 Terminate testing when a penetration of 0.25 in. (flow of 25) has been reached, or 10% of the sample height.

3.3 Record the peak shear resistance (CAR value) in pounds. For many 100% crushed fine aggregates, this will be the value at the time of termination (penetration of 0.25 in.).

Notes:

1. The influence of moisture absorption in this test procedure is mitigated if the components are mixed as soon as the 3.5% moisture has been added and then compacted immediately after mixing.

2. Using two pieces of non-absorptive specimen protection paper has been found to prevent the paper from sticking to the bottom of the compaction foot.

3. When compaction of the loose sample first occurs, the collapse of air voids in the loose mix causes fine particles to be vented along with air from the collapsing air voids. The fine particles tend to adhere to a lubricated hammer shaft and will cause drag on the sliding weight, which affects compactive effort. Tapping the sliding hammer on top of the compaction foot helps to collapse some of the air voids without forcefully ejecting aggregate particles.

It is recommended that the hammer shaft be cleaned and lubricated often.

Fines escaping from the edge of the specimen protection paper will adhere to the bottom of the compaction foot but are easily removed. Check the bottom of the compaction foot after each test specimen has been prepared.

4. When removing the protection paper, pry up one edge and slowly peel the paper backwards to prevent disturbing the compacted surface of the fine aggregate.

5. Use of a recording chart is recommended. The 5,000 lb setting works well for all materials. Some cubical limestone fine aggregates will exceed 5,000 lbs before reaching a penetration of 0.25 in. In these cases, record the CAR value as 5,000.